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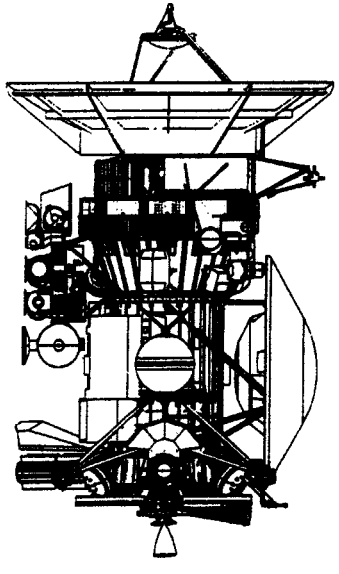
CASSINI TITAN FLYBY ENVIRONMENT THERMAL ACCEPTABILITY EVALUATION



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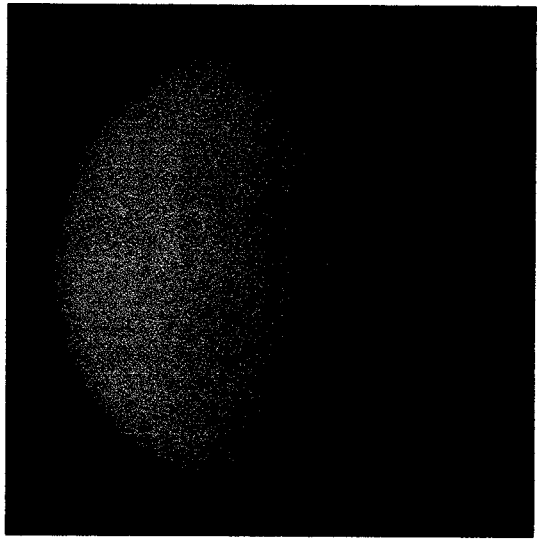

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INTRODUCTION

PROBLEM

- THE CASSINI SPACECRAFT (S/C) IS SCHEDULED TO PERFORM 45 TARGETED FLYBYS OF SATURN'S LARGEST MOON, TITAN, DURING ITS BASELINE SCIENCE TOUR
- TITAN IS APPROX. 40% THE DIAMETER OF THE EARTH AND HAS A PLANET-LIKE ATMOSPHERE DENSER THAN EARTH'S
- CURRENT RISK CONSTRAINTS, ENVIRONMENTAL PARAMETERS, AND OPERATIONAL SCENARIOS HAVE CHANGED SINCE PRE-LAUNCH DESIGN VERIFICATION ANALYSIS
  - 25 TARGETED FLYBYS HAVE CLOSEST APPROACH (C/A) TARGET ALTITUDES BELOW 1292 KM AND ARE OF THERMAL CONCERN
  - MAJOR CONCERN IS FLYBY INDUCED FREE MOLECULAR HEATING (FMH)
- IF UNABLE TO FLY BY TITAN AS CURRENTLY PLANNED, WILL ADVERSELY IMPACT SCIENCE PLANNING, MISSION PLANNING, NAVIGATION, AND ATTITUDE CONTROL
- FLYBY THERMALLY INDUCED RADIOISOTOPE THERMOELECTRIC GENERATOR (RTG) OUTPUT POWER TRANSIENTS ARE A POWER MANAGEMENT CONCERN

SOLUTION

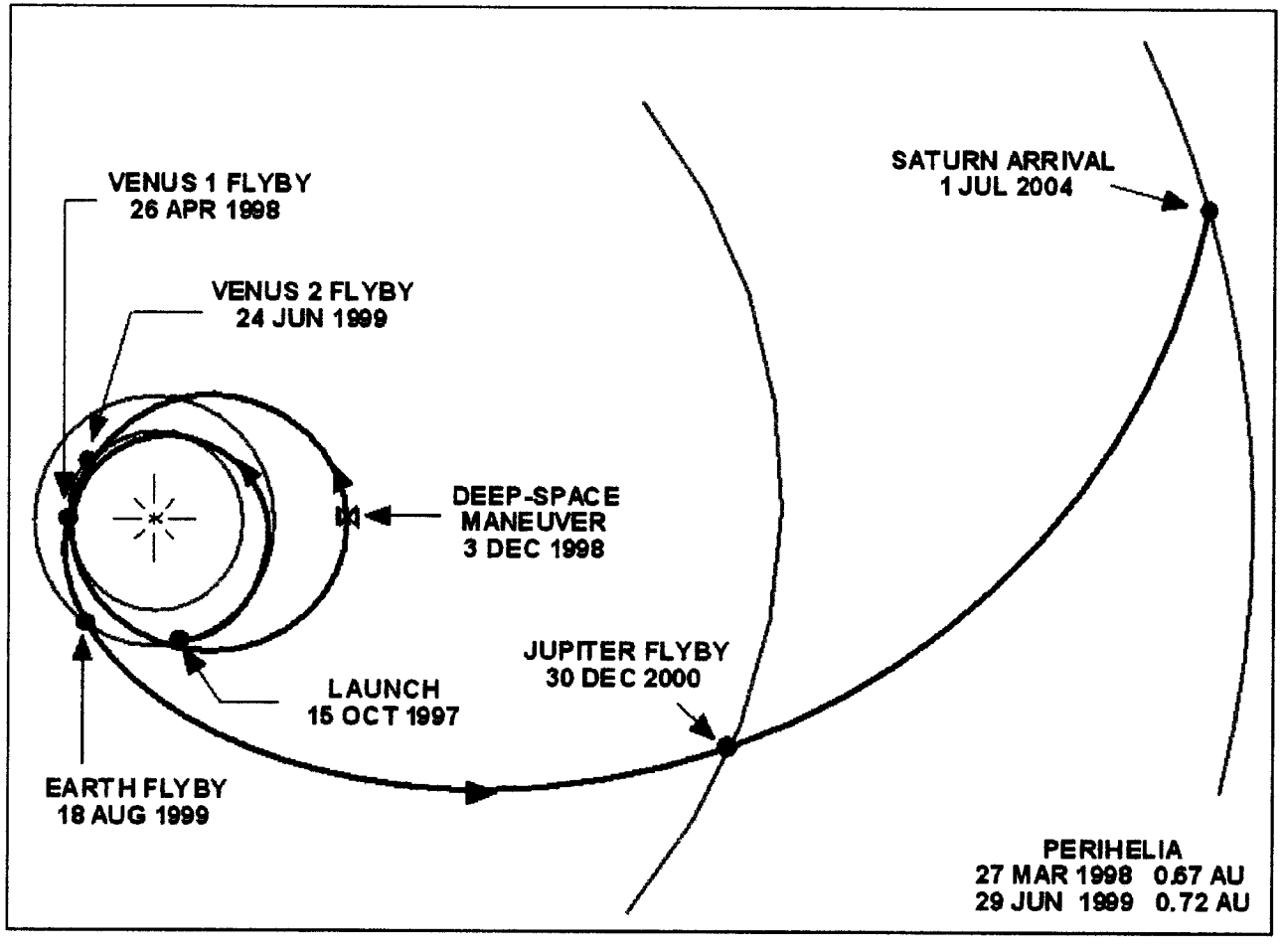
- PERFORM EVALUATION AND DEFINE THERMALLY ACCEPTABLE TARGET C/A ALTITUDES AND S/C ATTITUDES

INTRODUCTION (CONT'D)

SYSTEM-LEVEL APPROACH

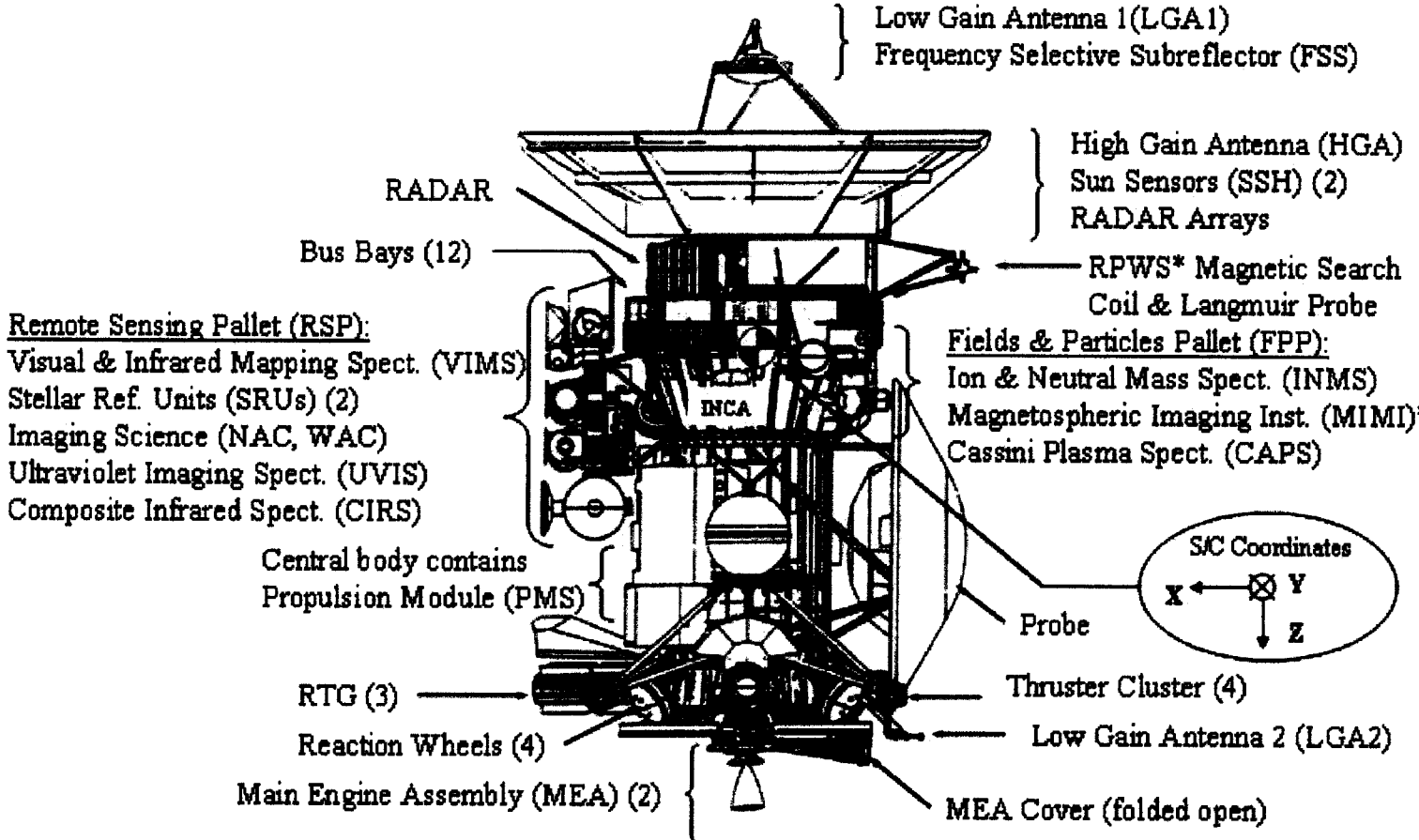
- THERMAL EVALUATION PERFORMED IN A STEP-BY-STEP METHOD IN CASSINI MISSION OPERATIONS BY THE SPACECRAFT OFFICE (SCO) THERMAL/DEVICES TEAM
  - DEVELOPMENT SUPPORT ARCHITECTURE NO LONGER EXISTS, BUT BENEFIT DERIVED FROM DEVELOPMENT LEGACY - PRE-LAUNCH DESIGN VERIFICATION
  - BENEFIT FROM OPERATIONS - S/C PERFORMANCE, ANALYSIS CAPABILITY
- TAKE ADVANTAGE OF CASSINI MISSION OPERATIONS "TEAM" ARCHITECTURE
  - WORK PROBLEM IN "TEAM-WORK" FASHION WITH OTHER ORGANIZATIONS TASKED WITH TITAN FLYBY ISSUES - SCIENCE COMMUNITY, MISSION PLANNING, SCO NAVIGATION (NAV), AND SCO ATTITUDE CONTROL (AACS)
  - CONSISTENLY INTERPRET PROJECT POLICIES AND REQUIREMENTS AND RESOLVE RISK, ATMOSPHERE MODEL, FLYBY TRAJECTORIES, UNCERTAINTIES, ATTITUDE SCENARIOS, AND POWER PROFILES
- SCO THERMAL/DEVICES TEAM MUST ACCOMPLISH:
  - MODEL ADAPTION, ENVIRONMENTAL HEAT LOAD GENERATION, PREDICTIONS, ANALYSIS, REPORTING, AND PROCESS AUTOMATION
  - SKILLS RETENTION - RETAIN CAPABILITY DEVELOPED IN THIS EVALUATION

CASSINI CRUISE TRAJECTORY PROMOTES ROBUST S/C THERMAL DESIGN



S/C DESIGNED TO WITHSTAND HELIOCENTRIC DISTANCE VARIATION OF 0.61 AU TO 10 AU

RSP HARDWARE THERMALLY MOST VULNERABLE REGION OF S/C CONFIGURATION



Note: *Radio & Plasma Wave Science Inst. (RPWS) and Cosmic Dust Analyzer (CDA) are on +Y side of spacecraft.
**MIMI is composed of the Charged-Energy Mass Spect. (CHEMS) and Low Energy Magnetospheric Measurement System (LEMMS) on the FPP, and the Ion and Neutral Camera (INCA) on the -Y side of the spacecraft.
Boom with Fluxgate and Vector/Scalar Helium Magnetometers is on +Y side of spacecraft mounted above Bus.

HIGHLIGHTS OF S/C THERMAL DESIGN

- MAJORITY OF S/C COVERED WITH MULTI-LAYER INSULATION (MLI) BLANKETS - REDUCES THERMAL SENSITIVITY TO VARYING ENVIRONMENTS
- LOUVERS USED ON BUS, RSP, AND FPP - REDUCES THERMAL SENSITIVITY FOR SELECTED TEMPERATURE RANGES
- HEATER POWER REQUIREMENTS MINIMIZED BY USE OF RADIOISOTOPE HEATER UNITS (RHUs), VARIABLE RHUs (VRHUs), AND RTG WASTE HEAT
- REPLACEMENT AND SUPPLEMENTAL HEATERS AND PASSIVE RADIATORS USED WHERE REQUIRED TO MAINTAIN TEMPERATURE LEVELS
- PROPORTIONAL PERFORMANCE HEATERS USED IN CERTAIN INSTRUMENTS TO REDUCE TEMPERATURE SENSITIVITY TO VARYING HEAT LOADS
- HGA THERMALLY ISOLATED FROM BUS AND DESIGNED AS SOLAR SHADE
- PROBE SIDE (-X) OF S/C DESIGNED TO TOLERATE SOLAR HEATING FOR OFF-SUN MANEUVERS INSIDE 5 AU – OFF-SUN DURATION HELIOCENTRIC DISTANCE DEPENDANT
  - PROBE IS RELEASED BEFORE THIRD TARGETED TITAN FLYBY
- RSP ORS AND SRU INSTRUMENTS SHADED FROM SUN INSIDE 5 AU

CASSINI SPACECRAFT - ORBITER AND PROBE

POLICIES, REQUIREMENTS, AND CONSTRAINTS

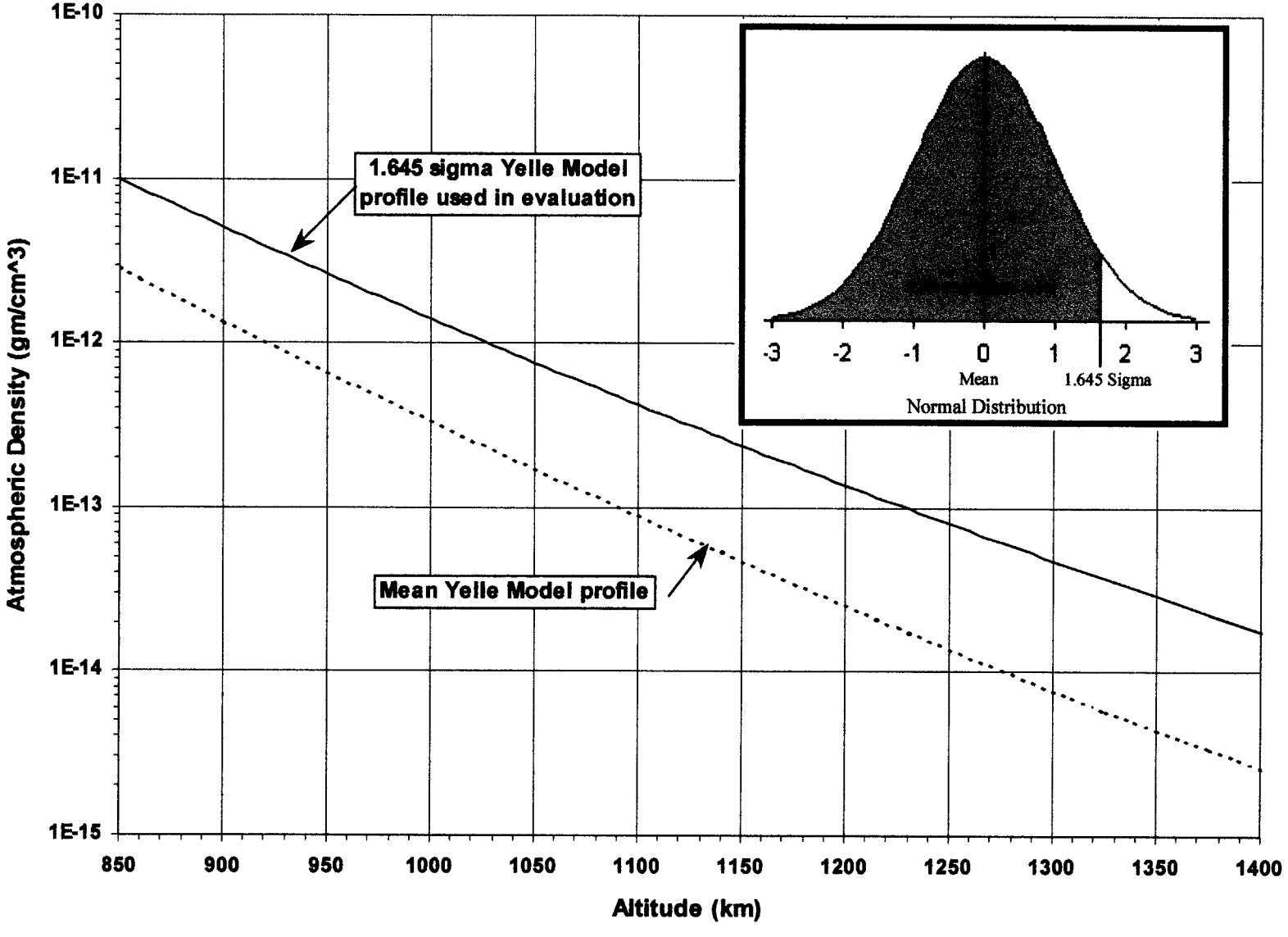
- RISK TO HARDWARE RESULTING IN TEMPORARY PERFORMANCE DEGRADATION DUE TO FLYING THROUGH THE TITAN ATMOSPHERE SHALL EQUAL 5%
- MISSION DESIGN SHALL NOT INCLUDE TITAN FLYBY TARGET ALTITUDES LOWER THAN 950 KM, OR AS COMPATIBLE WITH REVISED ATMOSPHERIC MODELS AND RISK
- INSTRUMENTS MUST WITHSTAND FOLLOWING SUN EXPOSURE* AT HELIOCENTRIC DISTANCE OF 0.61 AU:
  - WITH BORESIGHTS ALONG -Y AXIS, CONTINUOUS SUN EXPOSURE DURATIONS WITHIN SPECIFIED HALF CONE FIELDS-OF-VIEW: 7 S AT 4.3 MRAD, 18 S AT 23 MRAD, 23 S AT 32 MRAD, 30 S AT 44 MRAD, 105 S AT 175 MRAD
  - WITH RADIATORS NORMAL TO THE +X AXIS: 360 S OF EQUIVALENT CONTINUOUS SUN NORMAL TO THE RADIATOR SURFACES

  * FMH CAN BE CONVERTED TO EQUIVALENT SOLAR HEAT LOAD FOR COMPARISON
- S/C HARDWARE MUST STAY WITHIN FLIGHT ALLOWABLE TEMPERATURE RANGES
- FLIGHT RULES FURTHER CONSTRAIN SUN EXPOSURE FOR RSP ORS INSTRUMENTS - ENFORCED BY ONBOARD ATTITUDE CONTROL CONSTRAINT MONITOR

APPLIED UNCERTAINTIES

- ALL 45 TARGETED FLYBY HYPERBOLIC TRAJECTORIES PROVIDED BY SCO NAVIGATION
  - 3 σ (3 STANDARD DEVIATIONS) APPLIED TO TARGET C/A ALTITUDES = 30 KM
  - TOUR WORST-CASE (HIGHEST) C/A VELOCITY RELATIVE TO TITAN = 6.426 KM/S
    - RESULTS FROM RELATIONSHIP BETWEEN C/A ALTITUDE AND VELOCITY
  - LINEAR FLYBY TRAJECTORIES ASSUMED RATHER THAN HYPERBOLIC – WORKAROUND FOR SOFTWARE LIMITATIONS AND TO SIMPLIFY CALCULATIONS
    - TYPICAL HEAT LOAD ERROR RESULTS IN FRACTION OF 1°C ERROR IN RESULTS
  - ASSUMED NO ERRORS IN POSITION VECTORS FOR EARTH AND SUN
- YELLE MODEL OF TITAN ATMOSPHERE ADOPTED FOR USE BY CASSINI PROJECT
  - 1.645 σ APPLIED TO MEAN DENSITY PROFILE FOR 95% CONFIDENCE LIMITS
    - BASED UPON AREA UNDER STANDARD NORMAL DISTRIBUTION ASSUMING ALL 5% RISK ON HIGH END OF DISTRIBUTION ONLY
    - CALCULATED ASSUMING TEMPERATURE VARIES LINEARLY WITH σ - PER YELLE
- THERMAL MATH MODEL UNCERTAINTY TYPICALLY ± 5°C IN BULK NODES, ± 2°C IN HIGH RESOLUTION NODES

YELLE MODEL OF TITAN ATMOSPHERE DENSITY PROFILE



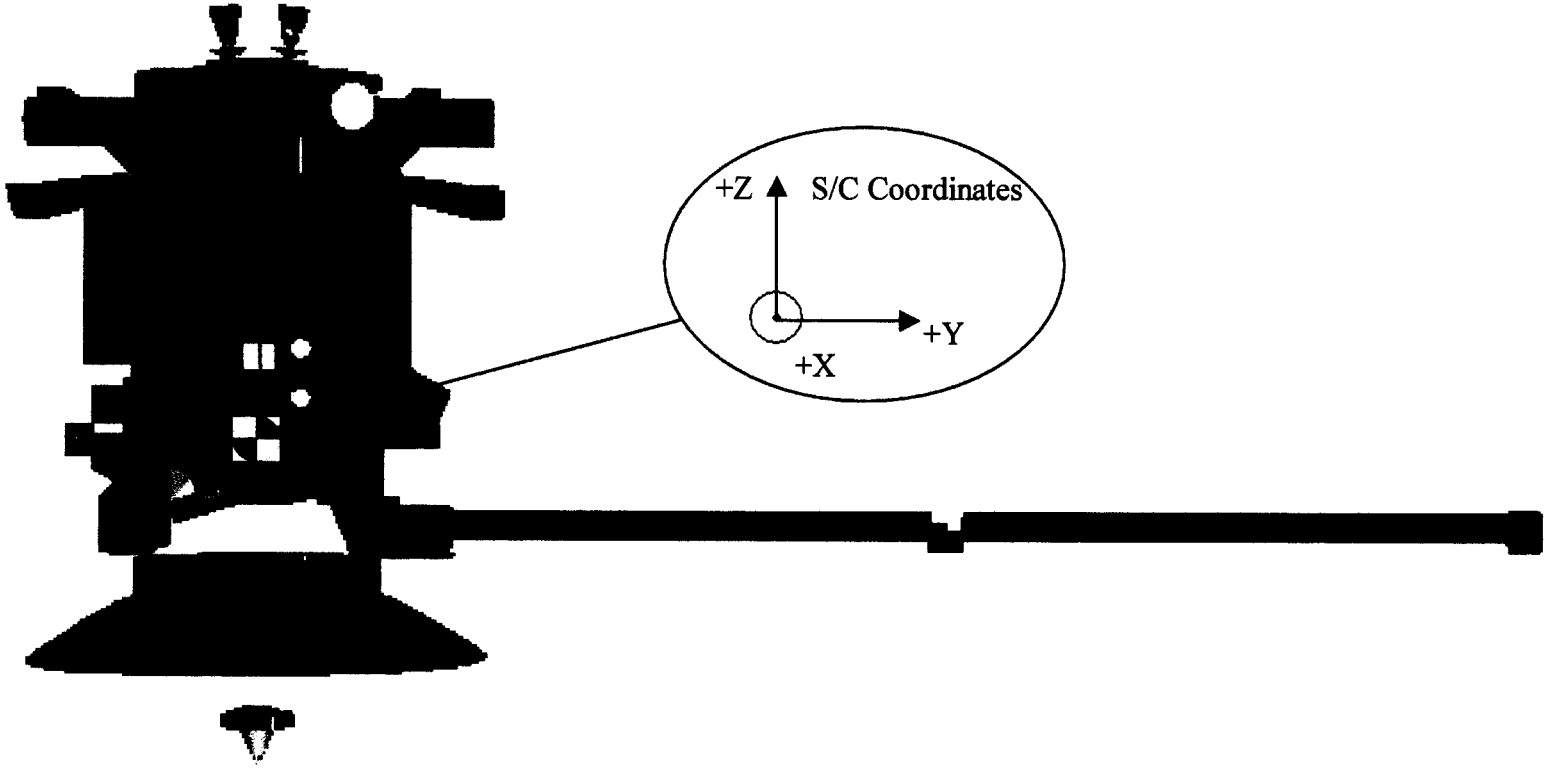
S/C WILL OPERATE USING POWER MODES

- A GROUP OF FUNCTIONS FOR AN OPERATIONAL ACTIVITY AND THE ASSOCIATED POWER USAGE IS REFERRED TO AS A POWER MODE
  - DURING TOUR THE S/C FUNCTIONS WILL BE GROUPED BASED UPON NEEDED FUNCTIONS FOR TYPE OF OPERATIONAL ACTIVITY BEING PERFORMED
  - EACH GROUP OF FUNCTIONS FOR AN OPERATIONAL ACTIVITY WILL DEFINE THE HARDWARE STATES THROUGHOUT S/C AND THE POWER USAGE
- TWO OPERATIONAL POWER MODES WILL BE USED FOR TITAN FLYBYS:
  - ORS(RCS)*: ORS AND MAPS INSTRUMENTS ACTIVE, RADAR AND RADIO SCIENCE (RSS) ARE OFF
  - RADAR(RCS)*: ORS INSTRUMENTS ARE ON BUT NOT ACTIVE, MAPS INSTRUMENTS ARE ACTIVE, RADAR IS ACTIVE, AND RSS IS OFF
  - * RCS REFERS TO ATTITUDE CONTROL AUTHORITY PROVIDED BY THRUSTERS
- AN ONBOARD FAULT CAN RESULT IN SYSTEM FAULT PROTECTION (SFP) PUTTING THE S/C THROUGH A SAFING PROCESS
  - RECONFIGURES S/C TO SAFE STATES AND EARTH POINTS S/C FOR TELECOM
  - RESULTING S/C FUNCTIONS AND POWER USAGE CAN BE CONSIDERED A MODE
    - ALL INSTRUMENTS OFF AND RCS ATTITUDE CONTROL AUTHORITY

TITAN FLYBY SAFING CONSIDERATIONS

- SAFING CAN OCCUR AT ANY TIME - TWO FLYBY SCENARIOS REQUIRE EVALUATION
  - S/C HAS COMPLETED SAFING PROCESS PRIOR TO ENTERING TITAN ATMOSPHERE
  - S/C SAFES OR STILL TURNING TO EARTH POINTING WHILE IN TITAN ATMOSPHERE
- TAKES APPROX. 4 S FOR SAFING POWER RECONFIGURATION, BUT CAN TAKE UP TO APPROX. 720 S FOR COMPLETION OF TURN TO EARTH POINTING
- POSITION OF SUN AND EARTH UNIQUE FOR EACH FLYBY
- AACS WORKED WITH THERMAL/DEVICES TEAM TO SELECT A MINIMUM NUMBER OF CANDIDATE SAFING INERTIAL ATTITUDES FOR POTENTIAL USE FOR ALL 45 FLYBYS
  - CANDIDATE ATTITUDES SELECTED FOR BOTH THERMAL AND AACS REASONS
    - CONSIDERATION GIVEN TO UNIQUE ATTRIBUTES OF ALL 45 FLYBYS
  - FLYBY S/C MODEL IMAGES WERE CREATED AND USED TO SELECT MINIMUM NUMBER OF CANDIDATE ATTITUDES FOR FLYBY THERMAL SIMULATION
  - ADDITIONAL THERMALLY EXTREME ATTITUDES SELECTED FOR FLYBY THERMAL SIMULATION TO COMPLETE THERMAL UNDERSTANDING OF S/C RESPONSE
  - PROCESS REDUCED NUMBER OF ATTITUDES REQUIRING ACTUAL THERMAL SIMULATION TO ONLY 5 REALISTIC AND 4 EXTREME FLYBY ATTITUDES

EXAMPLE OF S/C GEOMETRIC MODEL CANDIDATE SAFING ATTITUDE IMAGE

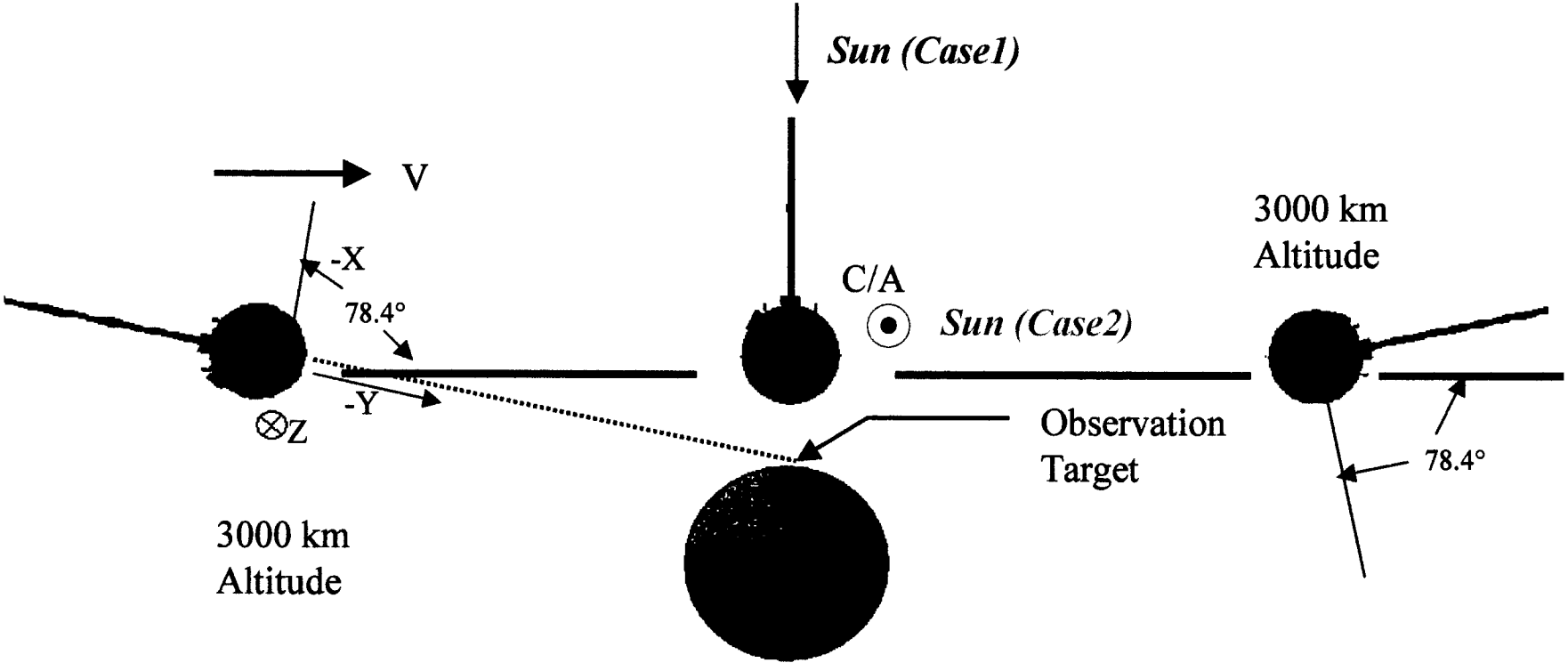


S/C MODEL IMAGE FOR FLYBY 42 WITH +X AXIS TO RAM AS VIEWED FROM A MOLECULE AT C/A POINT

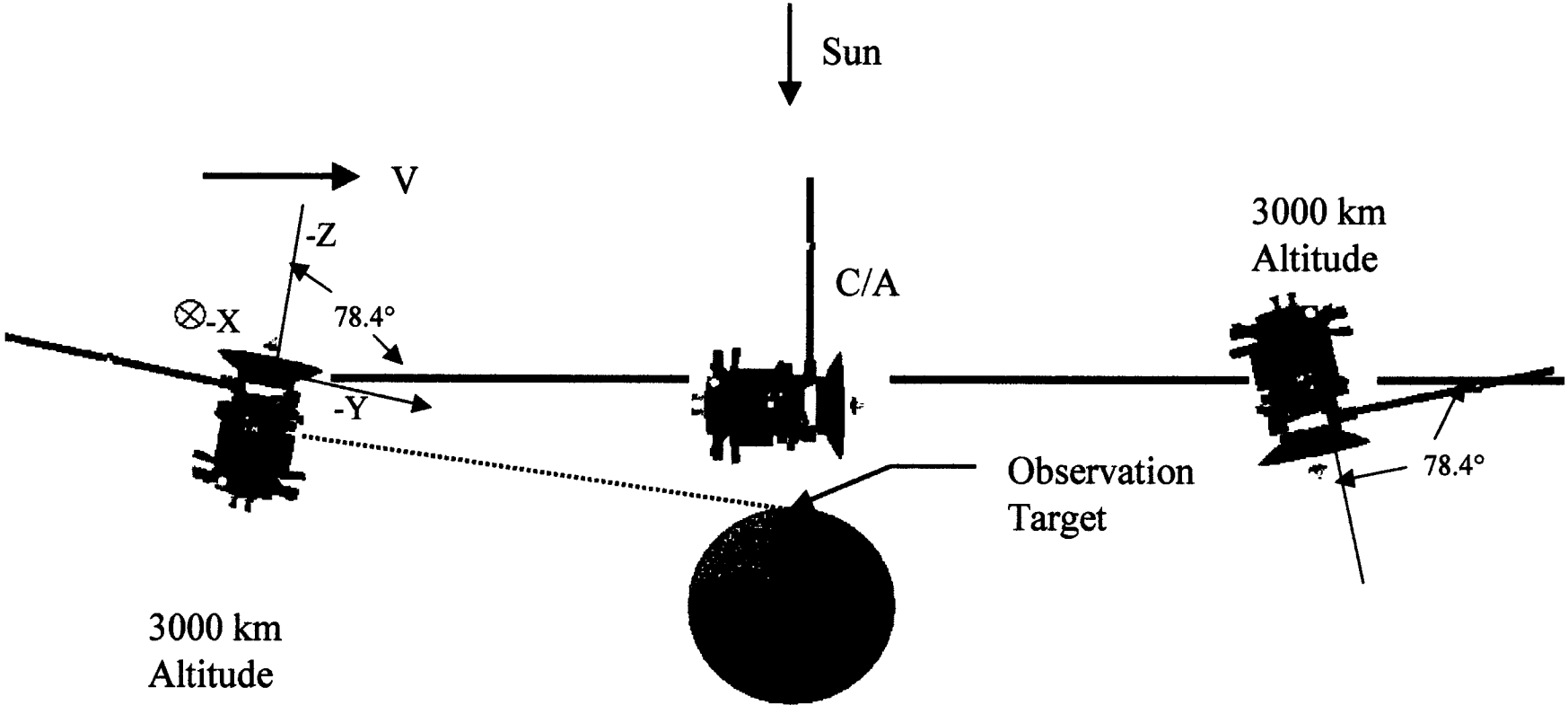
TITAN FLYBY OPERATIONAL CONSIDERATIONS

- AACS, MISSION PLANNING, AND THE SCIENCE COMMUNITY ALL CONTRIBUTED TO THE DEFINITION OF CURRENT OPERATIONAL FLYBY SCENARIOS
- TWO ORS IMAGING SCENARIOS REQUIRE THERMAL EVALUATION
  - IN BOTH THE ORS APERTURES POINT AT ONE SPOT ON TITAN THE ENTIRE FLYBY
  - S/C CAN ROTATE ABOUT EITHER THE X AXIS OR Z AXIS TO MAINTAIN POINTING
  - "SPOTLIGHT" POINTING AT THE SURFACE CLOSEST TO C/A POINT WAS CHOSEN AS IT CAUSED GREATEST EXPOSURE OF ORS INSTRUMENTS TO THE RAM
- A RADAR SCENARIO REQUIRES THERMAL EVALUATION
  - HGA APPROX. NADIR POINTED ENTIRE FLYBY WITH –X SIDE OF S/C LEADING
  - "SIDE-LOOK" SLEWING OCCURS WHERE S/C ROTATES ABOUT X (± 10°) AND Z AXES
    - DEGREE OF ROTATION ABOUT Z AXIS (ROLL) GOVERNS EXPOSURE OF RSP TO RAM. EXPECTED TO NOT EXCEED ± 10°, BUT SAFE ROTATION LIMIT MUST BE FOUND
- FLYBY S/C MODEL IMAGES WERE CREATED TO HELP EVALUATE FLYBY GEOMETRY
- 5 OPERATIONAL FLYBY THERMAL SIMULATIONS AND 7 THERMALLY EXTREME THERMAL SIMULATIONS USING 6 INERTIAL ATTITUDES WERE REQUIRED TO COMPLETE THERMAL UNDERSTANDING OF S/C RESPONSE
  - THERMALLY WORST FLYBY TRAJECTORY AND VARIOUS SUN POSITIONS USED

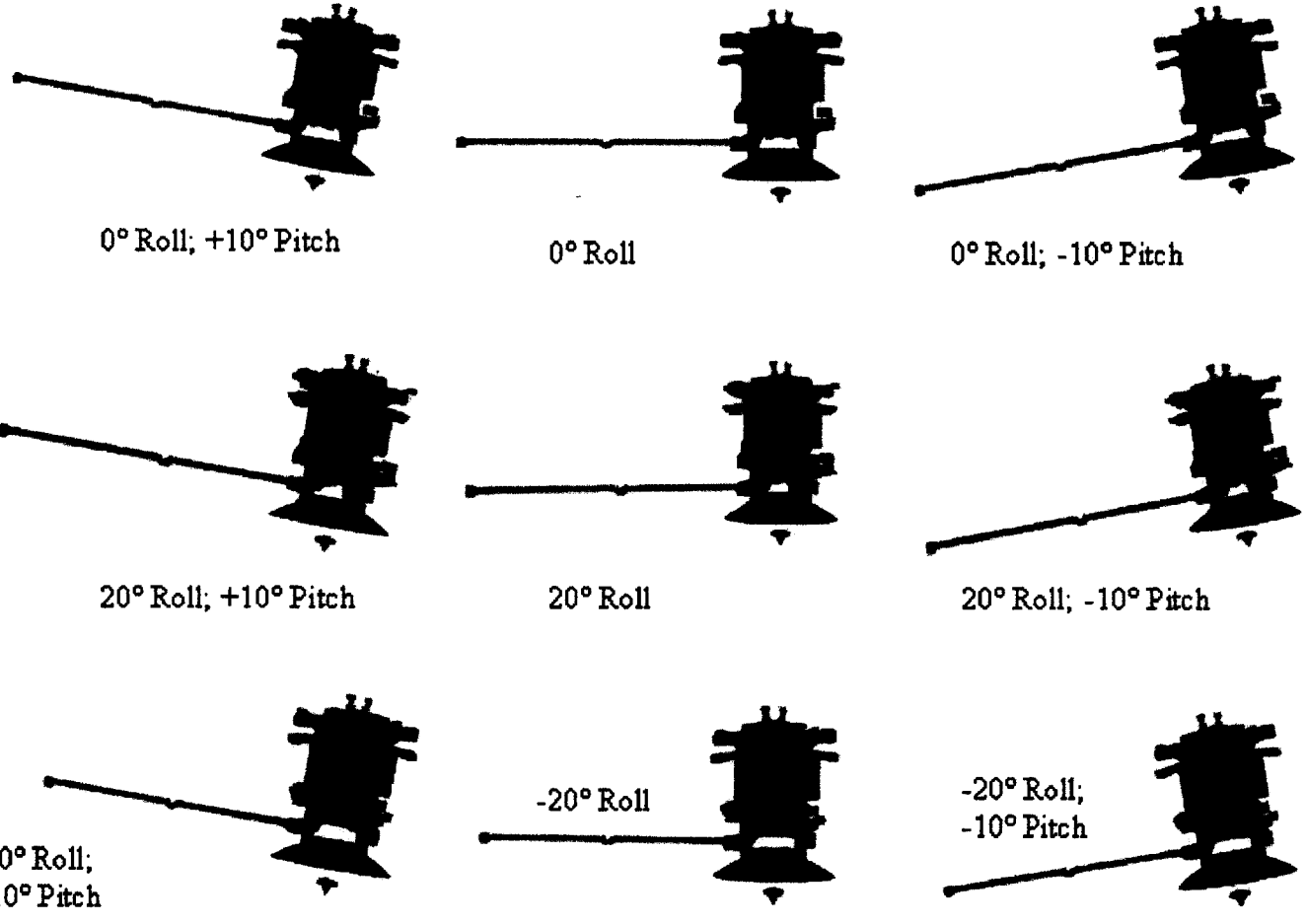
ORS "SPOT LIGHT" OPERATIONAL FLYBY WITH S/C ROTATION ABOUT Z AXIS



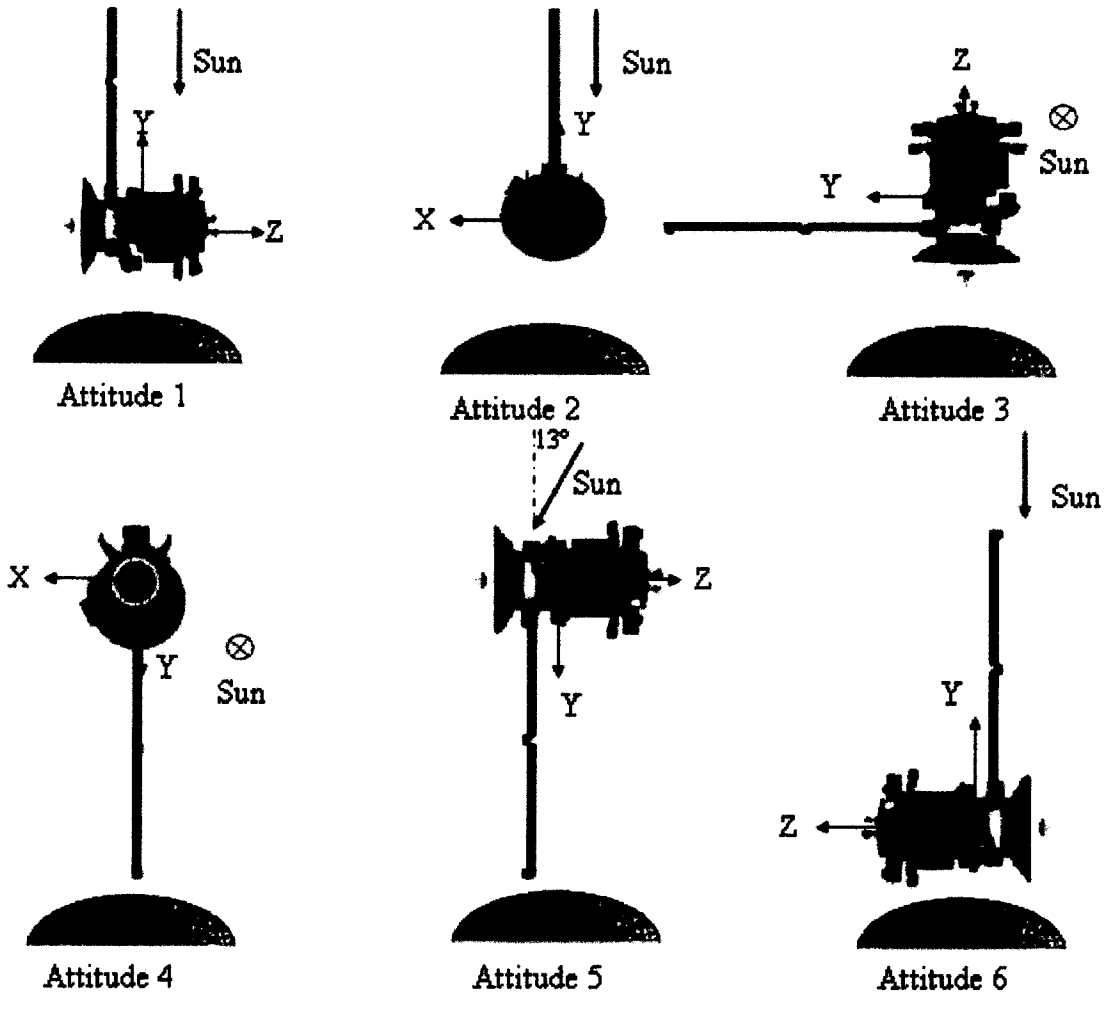
ORS "SPOT LIGHT" OPERATIONAL FLYBY WITH S/C ROTATION ABOUT X AXIS



RADAR OPERATIONAL FLYBY AT C/A SHOWING "SIDE-LOOK" SLEW VARIATIONS



SIX INERTIAL ATTITUDES USED FOR THE 7 INERTIAL FLYBY SIMULATIONS



THERMAL MODELING CONSIDERATIONS

- FLYBY THERMAL SIMULATIONS MODEL 3 HOUR PERIOD WITH C/A AT CENTER
  - FMH LASTS 20 MINUTES MAXIMUM (ALTITUDE DEPENDENT)
    - PEAK VALUES CAN BE COMPARABLE TO INCIDENT SOLAR AT 0.76 AU
  - TITAN IR AND ALBEDO COVER APPROX. 2 HOUR PERIOD CENTERED ABOUT C/A
    - INCLUDED IN ANALYSIS, BUT VIRTUALLY NEGLIGIBLE LEVELS
- USE FLIGHT CORRELATED, SYSTEM-LEVEL THERMAL MATH MODEL OF ENTIRE S/C
  - APPROX. 480 NODE THERMAL MODEL
  - APPROX. 570 NODE GEOMETRIC MODEL
- NODAL DIRECT SOLAR, TITAN IR, TITAN ALBEDO, AND FMH CALCULATED INDIVIDUALLY USING MONTE CARLO TECHNIQUES
  - DIFFUSE MULTIPLE SURFACE REFLECTIONS TAKEN INTO ACCOUNT
  - ASSEMBLY OF ENVIRONMENTAL HEAT LOADS INTO MODEL AUTOMATED BY SPREADSHEET
  - SOFTWARE NOT CAPABLE OF CALCULATING ALL FOUR HEAT LOADS TOGETHER
- MODEL IMAGES USED TO MINIMIZE THERMAL SIMULATIONS REQUIRED. COULD PRODUCE IMAGES OF S/C AT ANY POINT AND ATTITUDE FOR ANY TRAJECTORY.

THERMAL MODELING CONSIDERATIONS (CONT'D)

- SPREADSHEETS USED TO AUTOMATE LABORIOUS PROCESSES
  - ASSEMBLY OF THERMAL MODEL
  - FORMATTING OF TEMPERATURE OUTPUT INTO EASY TO EVALUATE FORMAT
- THERMAL ANALYZER SOFTWARE HAD ABILITY TO DISPLAY PLOTS OF NODAL TEMPERATURE TRENDS
- 1292 KM UPPER ALTITUDE LIMIT FOR THERMAL CONCERN EXCEPT DIRECT SOLAR AVOIDANCE CONSTRAINTS FOR +X AND –Y AXES.
  - VERIFIED BY SIMULATION AS A SANITY CHECK
- FOR SAFING SIMULATIONS ACTUAL TITAN FLYBY TRAJECTORIES USED.
- FOR OPERATIONAL FLYBYS WORST-CASE TRAJECTORY SIMULATED:
  - C/A TARGET ALTITUDE OF 950 KM (PLUS 3 σ UNCERTAINTY), C/A VELOCITY RELATIVE TO TITAN OF 6.426 KM/S, FMH ACCOMMODATION COEFICIENT OF 0.90, HELIOCENTRIC DISTANCE OF 9.05 AU, INCIDENT SOLAR FLUX VALUE OF 16.75 W/M^2, TITAN ALBEDO FACTOR OF 0.29, TITAN SURFACE IR IRRADIANCE OF 3.10 W/M^2
- LANGMUIR PROBE AND CLOSED MODEL OF MEA COVER TREATED WITH CONSERVATIVE HAND CALCULATIONS TO EXPEDITE EVALUATION

THERMAL EVALUATION RESULTS

SAFING FLYBYS

- THERMALLY ACCEPTABLE ATTITUDES FOUND SUCH THAT AACS WILL ONLY REQUIRE THREE ONBOARD ATTITUDE RECONFIGURATIONS FOR ALL 45 TARGETED FLYBYS
- C/A TARGETED ALTITUDES AS LOW AS 950 KM (PLUS 3 σ UNCERTAINTY) ARE ACCEPTABLE
- WHETHER SAFING IS COMPLETE PRIOR TO ENTERING ATMOSPHERE OR PROCESSES WITHIN ATMOSPHERE IS ACCEPTABLE

OPERATIONAL FLYBYS

- ATTITUDE CONSTRAINTS MUST BE APPLIED FOR RSP ORS INSTRUMENTS WITH RESPECT TO BOTH DIRECT SOLAR AND FMH
- OPERATIONAL SCENARIOS (ORS AND RADAR) EVALUATED ARE ACCEPTABLE AS LOW AS 950 KM (PLUS 3 σ UNCERTAINTY)
  - RADAR "SIDE-LOOK" SLEW ROLLS ABOUT Z AXIS CAN BE AS LARGE AS $\pm$ 20°

RTG OUTPUT POWER TRANSIENTS

- THE MAXIMUM TRANSIENT POWER DROP IN TOTAL RTG POWER OUTPUT EXPECTED (CAUSED BY FLYBY INDUCED TEMPERATURE TRANSIENTS) IS 5 W - WITHIN ACCEPTABLE POWER MARGIN

SKILLS RETENTION PLANNING

- ASSUME EVALUATION WILL BE REVISITED – RETAIN CAPABILITY ENTIRE BASELINE MISSION
  - SCIENCE PLANNING CONTINUES TO EVOLVE
  - FLIGHT EXPERIENCE MAY REVEAL NEW PROBLEMS OR OPPORTUNITIES
  - INFORMATION DATABASE MAY IMPROVE – ATMOSPHERE DENSITY MEASURED DURING FIRST TITAN FLYBY BY INMS INSTRUMENT
- SOFTWARE TOOLS, MODELS, AND SPREADSHEET CAPABILITY RETAINED IN USABLE FORM
  - DOCUMENTATION TO SIMPLIFY LATER USE CURRENTLY BEING ADDRESSED
  - SPREADSHEET AUTOMATION OF LABORIOUS TASKS EMPLOYED TO SIMPLFY USE
- RECOGNIZED PROBLEMS WITH CURRENT SOFTWARE TOOLS HAVE RESULTED IN SEARCH TO FIND AND ADAPT NEW TOOLS
  - THIS EFFORT IS CURRENTLY IN PROCESS
- MISSION DURATION (1997 TO 2008) MUST ACCOMMODATE PERSONNEL CHANGES
  - CAPABILITY BEING RETAINED BY SCO THERMAL/DEVICES TEAM

LESSONS LEARNED AND RECOMMENDATIONS

- PLAN DURING DEVELOPMENT PHASE TO PROVIDE CAPABILITY AND RESOURCES TO SUPPORT COMPREHENSIVE ANALYSES IN OPERATIONS
  - DEEP SPACE PLANETARY MISSIONS USUALLY LONGER THAN 4 YEARS
  - WORKFORCE TURNOVER MUST BE EXPECTED
- ABILITY TO RESPOND ANALYTICALLY IN OPERATIONS IS A FUNCTION OF MISSION DURATION
  - SHORT MISSIONS REQUIRE A RELATIVELY QUICK RESPONSE
- PLANNING SHOULD ACCOUNT FOR ARCHITECTURAL DIFFERENCES BETWEEN DEVELOPMENT AND OPERATIONS PHASES
- WELL UNDERSTOOD SYSTEM LEVEL MODELS SHOULD BE REQUIRED EARLY IN DEVELOPMENT PHASE FOR CORRELATION WITH SYSTEM-LEVEL TESTING AND EARLY FLIGHT
  - KNOWLEDGE RETENTION - DESIGN DETAILS CAPTURED IN MODEL
- OPERATIONS TEAMS SHOULD WORK TOGETHER FOR PROPER POLICY AND REQUIREMENT INTERPRETATION AND TO INSURE AWARENESS AND ACCURATE INFORMATION TRANSFER

LESSONS LEARNED AND RECOMMENDATIONS (CONT'D)

- REQUIRE THE USE OF CONSISTENT COORDINATE SYSTEMS AND THEIR TRANSFORMATIONS WITHIN ENTIRE PROJECT
- USE VISUALIZATION TOOLS TO CLARIFY ATTITUDE ISSUES AND EXPEDITE ANALYSIS EFFORTS
- DURING DEVELOPMENT PHASE SELECT SOFTWARE TOOLS THAT YOU ANTICIPATE WILL BEST MEET YOUR NEEDS DURING ENTIRE OPERATIONS PHASE
- ANALYSIS PROCESS MUST INCLUDE STEP-BY STEP SANITY CHECKS AND PEER REVIEWS TO PREVENT ERRORS AND UNCOVER SOFTWARE BUGS
- AUTOMATE PROCESSES TO EXPEDITE, SIMPLIFY, AND IMPROVE THE RELIABILITY OF CALCULATIONS, INTERFACE PRODUCTS, AND OUTPUT PRODUCTS
- DOCUMENT ANALYSIS PROCESSES AND TOOLS TO SIMPLIFY THE LEARNING AND REFRESHING CURVES DURING THEIR FUTURE USE - ASSUME THEY WILL BE USED AGAIN
- ASSUME SURPRISES WILL OCCUR - THE ABOVE ALLOWS A TEAM TO RESPOND SUCCESSFULLY AND IN A TIMELY FASHION